Chapter 2

History of Aquaculture

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For purposes of this historical account the concentration is on finfish, shrimp, and mollusks that are reared as food for human consumption. The reader should be aware that aquaculture is much more expansive. In the finfish category alone there is a considerable amount of culture of ornamental fishes, particularly freshwater species. There is also a good deal of interest in marine ornamentals but the number of species that have been successfully cultured is considerably smaller than is the case for their freshwater counterparts. In some parts of the world there is also aquaculture of baitfish, such as minnows, for marketing to the recreational fishing community.

There are a large number of mollusks, crustaceans, and other invertebrate groups that include species currently being produced in aquaculture. Oysters, clams, mussels, and abalone are examples of mollusks being cultured, while various species of marine shrimp and one species of freshwater shrimp, *Macrobrachium rosenbergii,* are the most important groups of crustaceans being cultured for the human food market. Crabs are also cultured to a limited extent, and there is some culture of lobster. There is also some culture of sea urchins and sea cucumbers as well as a few other invertebrates.

Captive spawning and rearing of fingerlings for stocking recreational fishing waters has a relatively long history. The foundations upon which the science of aquaculture are based can be traced in large part to the pioneering fish culturists who developed the various processes associated with spawning and rearing a variety of both marine and freshwater fishes. Fish continue to be produced

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for recreational purposes but there are also hatcheries producing fish in many countries to enhance wild capture fisheries. Japan has a history over the past several years of also producing shrimp for enhancement stocking.

Ocean ranching is another form of aquaculture. It most commonly involves salmon that are released from hatcheries as smolts to find their way to the ocean where they grow to maturity and then return to their natal waters to spawn. Some of the returning fish are used as broodstock, with the majority being taken by commercial fishermen. In Japan, a modified form of ocean ranching has been developed with non-salmonid marine fishes. Young fish are trained in the hatchery to respond to a sound source at feeding time. Once the behavior is ingrained in the fish, they are released into the wild near a feeding station that emits the same sound that had been used for conditioning. Feeding continues using the sound attractant until the fish reach market size, after which they are captured for processing.

A variety of invertebrates are cultured as food for other cultured species. Examples are brine shrimp, rotifers, and copepods. Various species of phytoplanktonic algae are cultured as food for those invertebrates, thus requiring the aquaculturists to maintain at least three different culture systems: phytoplankton, zooplankton, and the fish or invertebrate species that will ultimately be marketed.

Phytoplanktonic species are not the only members of the plant kingdom that are being cultured. Macroscopic algae are also of interest to aquaculturists. For example, nori is used to make sushi wrappers and is also used in other products that are consumed by people. A few higher plants, such as water chestnuts, are also cultured for human consumption.

In most cases invertebrates and aquatic plants have a long history of consumption by humans but a relatively short history of being cultured. Most of that culture activity began in the twentieth century. One notable exception is oysters, which were apparently cultured during the days of the Roman Empire nearly 2,000 years ago (Beveridge & Little 2002).

Hydroponics is another form of aquaculture in which terrestrial plants are grown in nutrient-enriched water. Various vegetables can be grown hydroponically and the approach has been used in conjunction with fish or invertebrate aquaculture in polyculture.

2.1 Beginnings of aquaculture

The dawn of aquaculture is shrouded in mystery, although most who have delved into that history agree that the art of aquaculture began in China. Various authors have indicated that the beginnings of aquaculture can be traced as far back as 3,500 to 4,000 years Before Present Era (BPE). Among them were Hickling (1962, 1968), Rabanal (1988), Bardach *et al.* (1972), and Ling (1977). Jessé & Casey undated posited that aquaculture may go as far back as 5,000 years BPE. The latter indicated that pond culture of grey mullet (*Mugil cephalus*) and carp (presumably common carp, *Cyprinus carpio*) began with the first of China's

Emperors in the period from 2852 to 2737 BPE, but provided no details on the source of that information. Ling (1977) indicated that carp culture developed from simply catching and holding fish in baskets to holding them in traps and finally, feeding them to grow them to larger sizes before harvesting.

While the precise period when aquaculture developed in China may be in question, there is general agreement that the first published work on the subject was a small volume by Fan Li that appeared about 475 BPE (for example, see Borgese 1980). Ling (1977) indicated that Fan Lee described how to spawn fish including how to select ripe brooders. Pillay & Kutty (2005) indicated that Fan Li was a politician turned fish culturist and that he made his fortune growing fish. Other early Chinese publications on collecting carp fry from rivers and rearing them in ponds were also produced according to Pillay & Kutty (2005).

Ling (1977) reported that when the Lee Dynasty was founded in 618 BPE, a thousand years or more of common carp culture was threatened. That was because the word Lee is pronounced the same as lee, which was the word used for carp. It was considered sacrilege to catch and eat lee because it was an insult to the Emperor. To get around the problem, culture methods for grass (*Ctenopharyngodon idella*), silver (*Hypophthalmichthys molitirix*), bighead (*Aristichthys nobilis*), and mud carp (*Cirrhinus molitorella*) were developed, which led to polyculture.

If one follows the chronology of aquaculture development produced by Jessé & Casey undated, the Egyptians may have developed some form of aquaculture at about the same time as the Chinese. Those authors attribute Egyptian hieroglyphics that appear to show pond culture being developed between 2357 and 1786 BPE. Another source places the Egyptians practicing intensive fish culture during the period 2052 to 1786 BPE, corresponding with the Middle Kingdom period (Anonymous, undated). In addition to reports of hieroglyphics depicting fish culture, a bas relief from the tomb of Thebaine, an Egyptian nobleman, depicts some type of tilapia being fished from an artificial pond (Chimits 1957). That bas relief was redrawn and also mentioned by Beveridge & Little (2002) as well as Pillay & Kutty (2005). Another bas relief from around 2500 BPE was reproduced in a book by Maar *et al.* (1966) that shows a pond with a variety of fish, at least one of which appears to be tilapia.

2.2 Expansion prior to the mid-1800s

Common carp culture was introduced from China to various parts of Southeast Asia by Chinese immigrants (Ling 1977). Carp appear to have been raised in ponds in Japan at least 1900 years ago (Drews 1951). However, fish culture was not important in Japan before the seventeenth century.

The Romans reportedly introduced carp from Asia Minor into Greece and Italy (Maar *et al.* 1966). The Romans also appear to have introduced common carp culture to England during the first century BPE (Beveridge & Little 2002). Carp culture was said by the same authors to have been established in central Europe by the seventh century. Pillay & Kutty (2005) indicated that carp culture

was initiated when the fish were introduced to monastery ponds which occurred in the Middle Ages in western and central Europe (Beveridge & Little 2002). Over the centuries carp culture expanded throughout much of Europe. Today, the culture of various species of carp accounts for about 80% of the aquaculture production from marine and freshwaters in central and Eastern Europe (Szücs *et al.* 2007). Worldwide, carp and other cyprinids clearly dominate world production with respect to weight of cultured finfish produced (FAO 2006), with most of that production taking place in China.

Carp culture appears to have been conducted on at least part of the Indian subcontinent since the eleventh century (Pillay & Kutty 2005). The tradition in India has always been to culture the local carp species catla (*Catla catla*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus mrigala*).

Brackishwater aquaculture in Southeast Asia reportedly began during the fifteenth century, probably in Indonesia (Pillay & Kutty 2005). Milkfish were produced at that time in coastal ponds called tambaks. Milkfish culture expanded to other parts of Southeast Asia including the Philippines and Malaysia, which continue to be major producing nations. Mullet also were probably produced in Southeast Asia 1400 years BPE (Ling 1977). Pillay & Kutty (2005) placed the origins of walking catfish (*Clarias* spp.) culture in Cambodia.

Native Hawaiians had been growing fish in ponds for as long as 500 years before the Hawaiian Islands were discovered by Captain James Cook in 1778. The Hawaiians would allow seawater to enter their ponds with the rising tide, then block off the pond entrances thereby trapping whatever creatures were present. The animals would then be allowed to grow to harvest size (Costa-Pierce 2002).

Trout were among the early groups of fishes to be cultured in Europe. Davis (1956) attributed the first successful artificial insemination of trout eggs to a monk in France who lived in the fourteenth century. Over the centuries, trout culture spread across much Europe and, ultimately, around the world. The European brown trout (*Salmo trutta*) was the subject of the early activity, though rainbow trout (*Oncorhynchus mykiss*) introduced from North America ultimately became more popular with fish culturists. The British introduced trout to some of their colonies in Asia and Africa mainly for recreational fishing (Pillay & Kutty 2005).

2.3 The explosion of hatcheries

While fish culture expanded over the centuries that followed the middle ages, that expansion was largely restricted to a small number of species and often depended largely on the capture of wild fry or fingerlings that were then confined for growout. Milkfish is an excellent example and that industry still relies largely on wild captured fry.

In the latter half of the nineteenth century, enthusiasm for recreational fishing coupled with increasing numbers of reports that many freshwater and marine stocks were being negatively impacted by overfishing, led to the development

Figure 2.1 State of Oregon railroad car used to transport fish.

of private and public hatcheries in Europe and North America. In the United States the initiative began when several states in the northeast established fish commissions that were charged with managing their fisheries. Some of the commissions turned to stocking as a means of enhancing their recreational fisheries. In most cases they initially turned to private fish producers to supply the fish, most commonly brook trout (*Salvelinus fontinalis*).

In 1872, the United States Commission on Fish and Fisheries was established by Congress and Spencer F. Baird, who conceived the idea and was named the first Commissioner. Baird was concerned about declining fish populations and directed a lot of the activity of the Commission toward developing hatcheries for both freshwater and marine species. As a result, over a period of several decades billions of eggs were hatched and their fry were distributed by the United States Commission on Fish and Fisheries, which later became the United States Bureau of Fisheries, Bureau of Commercial Fisheries, and, ultimately, the National Marine Fisheries Service (Stickney 1996a–e, 1997a–c). Millions of railroad miles passed under the wheels of cars hauling fish, first by the United States Commission and soon followed by state fish commissions or fisheries agencies (fig. 2.1). Hatcheries on the east coast produced Atlantic salmon (*Salmo salar*) for shipment to the west coast and hatcheries on the west coast (initially in northern California and later in Oregon and Washington) produced Pacific coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) for shipment to the east. While no survival of salmon appears to have occurred in either case, hundreds of millions of eggs and fry were involved in the effort. This may be due to

the natural tendency of smolts would be to turn the wrong direction if they survived long enough to reach the sea. It wasn't only salmon that were involved in the transfers. There were also largemouth bass (*Micropterus salmoides*), walleye (*Stizostedion vitreum vitreum*), cod (*Gadus morhua*), rainbow trout, and striped bass (*Morone saxatilis*), to name but a few. Striped bass from the east became established in California and continue to thrive there. Baird's successors continued to expand the numbers of hatcheries and species produced. Baird himself promoted the introduction of common carp into United States waters perhaps thinking that many of the European immigrants who made up a large percentage of the population at the time would have a preference for a species from their native countries with which they were familiar. The Commission stocked carp around the nation and territories but discontinued the process after only a few years because the waters were soon teeming with reproducing populations. Ultimately, carp were seen by most Americans as trash fish and their introduction is not generally considered to be one of Baird's crowning achievements.

Of the billions or perhaps trillions of eggs and larvae of marine species and some freshwater species that were stocked during the 1800s, there is little or no evidence of survival. The fish culturists of the late nineteenth and much of the twentieth century were unsuccessful in finding ways to feed the very tiny fry that are so common among marine species and the animals were typically released before their digestive systems were developed. The same was true for freshwater fishes with small eggs. Salmon and trout were exceptions in that they had large eggs and fry that survived on a yolk sac for an extended period following hatching. When they did begin exogenous feeding, the fry were more advanced and it was possible to successfully provide them with food of one kind or another—chicken egg yolk being one popular item. Details of this fascinating period of fish culture development in the United States can be found in a book by Stickney (1996a).

2.4 Art becomes science

It wasn't until the mid-twentieth century that the art of aquaculture developed into what exists today as a complex multidisciplinary science that now features over 200 species under culture (including invertebrates as well as finfish). However, significant progress in the development of the techniques required to spawn and rear a variety of species had been developed by the end of the nineteenth century as detailed by Bowers (1900). In fact, if one compares a hatchery from the late nineteenth century with one of today and overlooks modern materials such as fiberglass, PVC plumbing, electric pumps, and all sorts of electronic gadgets and just looks at the basics, it is not difficult to imagine that someone from the time of Spencer F. Baird would recognize a lot of what he would see. An earthen pond is still a pond. The linear wooden raceways of old are now fabricated of concrete, fiberglass, or aluminum and in many instances circular raceways have replaced linear ones, but the concept has not changed. I can see a Livingston Stone (who developed salmon and trout hatcheries in California in

the 1870s) as finding himself right at home as soon as he learned how to use a dissolved oxygen meter and become adjusted to a few other gadgets that didn't exist in his time.

It is not possible to put a precise date as to when the art became science as it was an evolutionary process. Each hatchery manager probably developed some new techniques and those were shared among peers at meetings such as those of the American Fish Culturists Association, which was established in 1870 and later became the American Fisheries Society.

In the United States, university courses associated with fish culture were rare before 1950, and any that existed would have undoubtedly focused on techniques associated with the culture of species for stocking, which would mean almost exclusively salmonids and non-salmonid freshwater species. The University of Washington in Seattle, Washington, established a position in fish culture in 1920 (Stickney 1989). Lauren Donaldson, who took a position at the university in 1932, constructed a salmon return pond on the campus and established a salmon run. Salmon were literally returning to the classroom.

Ichthyologic research was being conducted at many universities in the early twentieth century but the focus was usually not on aiding in the development of fish culture. It is probably safe to say that most of the applied fish culture research that was being conducted took place in government hatcheries where the methodology was probably of the trial and error variety. Since the approach involved producing fry and fingerlings for stocking public waters, there was not a great deal of interest by the government hatcheries in developing the technology associated with growout to foodfish size. Those relatively few private foodfish producers were largely on their own.

Today aquaculture courses (which typically include fish culture, but are usually not restricted to the study of finfishes) can be found at colleges and universities across the world. Certificate, undergraduate, and graduate programs abound. A quick search for "aquaculture institutions" on the Internet will provide page after page of hits.

While Hickling (1962, 1968) authored short books on fish farming, there was no comprehensive treatment of global aquaculture available until the classic book by Bardach *et al.* (1972) appeared. That work was based on the information gathered by the two senior authors who traveled the world looking at the status of aquaculture. The book provides good documentation of the state of the art that existed early in the third quarter of the twentieth century. Much of the aquaculture at the time was artisanal in developing countries, and artisanal aquaculture continues to provide much of the fish available to local communities in developing nations today (fig. 2.2).

Much of the published information on fish culture prior to the 1970s consisted of gray literature and in such government publications as *The Progressive Fish-Culturist*, which was published by the United States government for many years before being taken over by the American Fisheries Society. That publication is now being published as *The North American Journal of Aquaculture*.

The growth of information on commercial fish culture over the past few decades has been exponential. A large number of journals dedicated to

Figure 2.2 Artisanal tilapia pond in the Philippines (Photo by Robert R. Stickney).

aquaculture in the broad sense, fish culture, or one of the many aquaculture subdisciplines—nutrition, disease, engineering, genetics and water quality to name a few—have been established and the list continues to grow. Similarly, books on aquaculture and the various specialized branches of the field have proliferated.

The number of societies that are solely focused on aquaculture or include aquaculture within the broader context of fisheries and/or aquatic sciences has also expanded. The formation of the World Mariculture Society in 1969 (the name was changed to the World Aquaculture Society in 1986) was seen by some observers as an audacious move. How dare a small group of Americans (and one individual from Great Britain) gathered in the state of Mississippi have the gall to create a global organization? While initiated by a group of about forty, the society has thrived and came to live up to its name. It has been joined by a number of other regional or national societies (e.g., the European Aquaculture Society) and chapters, meetings of which often attract over 1,000 attendees. Virtually all of these associations or groups also publish a magazine or newsletter, many produce published proceedings of their meetings, and some also have developed book series. Such organizations typically have members or at least attendees at meetings from academia and government agencies as well as from the commercial production and supply sectors.

Specialty organizations that focus on a particular area of interest have also been formed. Examples are organizations devoted to the culture of channel catfish, tilapia, trout, salmon, engineering, and economics.

2.5 Commercial finfish species development

Commercial finfish culture was limited in the United States until rapid development began in the 1960s. Initially, species selection was often based upon local interest and availability (e.g., channel catfish, trout) but in many cases was also driven by declines in wild fisheries (e.g., Atlantic salmon, striped bass, cod, tuna) or finding alternatives to more traditionally consumed species (e.g., tilapia in the Americas). The following are some examples to illustrate how development took place with respect to a few species or species groups.

2.5.1 Channel catfish

The prediction that channel catfish (*Ictalurus punctatus*), which had been grown for stocking for many years, could be reared to market size and sold for a profit was first put forth in papers by Swingle (1957, 1958). Swingle speculated that a farmer would need to get US$1.10/kg at the farm gate to make a profit. Now, a half-century later, the farm gate value of the fish has not even doubled. The early work with channel catfish, as was true of many other native fish species being cultured in the United States, began at state and federal government hatcheries. Channel catfish were found to be difficult to spawn but success in pond spawning was finally achieved in the early twentieth century (Shira 1917). The species is native to streams where it spawns under logs, in depressions in riverbanks, or in some other convenient hiding place. Once the cavity spawning requirement was recognized and appropriate nests were placed in ponds, spawning became routine and is practiced today much like it was a century ago (Hargreaves & Tucker 2004).

It was in the state of Alabama where Swingle (1957, 1958) conducted his research that the industry was born. The history of catfish farming in that state was chronicled in a fascinating book by Perez (2006). After World War II, some farmers in the southern United States turned to fish culture. They were first interested in buffalo fish (*Ictiobus* sp.) and later turned to polyculture of buffalo fish with catfish. By the early 1960s, buffalo fish culture was on the way out and was being replaced with channel catfish monoculture (Hargreaves & Tucker 2004). Because of a lack of abundant ground water Alabama catfish farmers had to rely for the most part on precipitation runoff to fill their ponds. A seemingly much better situation with respect to water availability was seen in central Arkansas where rice had been the staple crop. Rice paddies could be fairly easily turned into catfish ponds on the flatlands of the region located to the north of the Ozark Mountains. The US Department of Interior set up one of two laboratories dedicated to fish culture research in 1958 when the Fish Farming Experimental Station was established in Stuttgart, Arkansas. The other laboratory was the Southeastern Fish Cultural Laboratory located in Marion, Alabama. The Stuttgart laboratory was moved to the Department of Agriculture in 1996 and became the Harry K. Dupree Stuttgart National Aquaculture

Research Center, named after a scientist who had been the director at both laboratories, first in Marion, and later in Stuttgart.

The first author of this chapter had the opportunity to spend the summer at the Stuttgart laboratory in 1969. It was at that time that the water table was dropping rapidly due to the massive withdrawals required to meet the needs of both the rice and catfish industries. Catfish farming was rapidly being developed in Mississippi, the state that quickly took over domination of the industry. However, Arkansas, Alabama, and Louisiana still produce considerable volumes of catfish with lesser amounts grown in many other American states.

Once popular only in the southern region of the United States, the demand for channel catfish is now nationwide due in part to an excellent marketing campaign that was launched during the rapid growth phase of the industry. Other factors that contributed to the growth of the industry included the formation of processing and feed cooperatives by the farmers that allowed them to share in the profits from those sectors of the industry while the farm gate value of the fish remained low.

One major problem affecting sector growth had been the seasonality of catfish availability. The fish require about eighteen months to grow from hatching to the typical harvest weight of about 0.5 kg. Initially, harvests occurred in the fall and were associated with complete draining of the ponds. In response to the market demand for year-round availability of fresh catfish, the procedure was changed to one in which partial harvesting is practiced at intervals throughout the year. Fingerlings are added to replace the fish that are harvested in a process known as understocking. The ponds are not drained during the harvesting process. Seines of certain mesh sizes selectively harvest the size of fish that the buyer prefers. Those of the preferred size—which can vary depending upon the market to which the fish are to serve—are loaded on trucks for live-hauling to the processing plant and those not needed are released back into the open pond. Ponds are often operated in this manner for several years without being drained.

The 1970s was a period of consolidation as the number of farms was reduced while the area under culture increased greatly as many farmers failed and the successful ones expanded their holdings (Hargreaves & Tucker 2004). Government and university research led to the development of high-quality formulated feeds containing little or no fish meal or other animal protein; it also addressed various disease problems, developed aeration devices that effectively maintain dissolved oxygen in heavily stocked ponds, and addressed a series of other issues that faced the industry. Off-flavor was (and continues to be) a major issue particularly during the warm months. A process has been developed whereby a few fish from a pond scheduled for harvest are taken to the processing plant for taste testing a week or two in advance of harvesting, the day before and when the truckload of fish reaches the processing plant. If the fish have off-flavor (often described as an earthy-muddy flavor), they are rejected. Blooms of certain algae are the source of the chemicals that cause the off-flavor, and given time, the blooms will dissipate and the fish will metabolize the off-flavor producing chemicals.

In 2005 the industry produced 275,757 metric tonnes of channel catfish, down from the high of over 300,000 metric tonnes in 2003. Production has continued

to fall with the 2007 production estimated at 224,500 to 229,000 metric tonnes (Anonymous 2008). According to the National Agricultural Statistics Service (NASS 2008), the amount of channel catfish processed through November 2008 was up several percent over 2007. Imported basa (*Pangasius bocourti*) from Vietnam compete with channel catfish in the marketplace and for some time were available at a lower price. A regulation was put in place that prohibits marketing of basa as catfish in the United States. In addition, and more broadly, the United States has adopted country of origin labeling (COOL) on imported fishery products. Those regulatory changes may have contributed to increases in the price of basa relative to that of channel catfish.

Brazil is also now producing channel catfish, some of which are exported from that country to the United States. China is also growing channel catfish and sent over 260,000 kg to the United States in 2007 (NASS 2008). Imports of frozen basa and channel catfish to the United States during the first nine months of 2007 amounted to 28,760 tonnes (Anonymous 2008). Other nations that export catfish of various species to the United States include Cambodia, Indonesia, Malaysia, Spain, and Thailand (NASS 2008). The plight of catfish farmers from foreign competition has been exacerbated by current high feed costs. Still, channel catfish represent the largest component of commercial fish farming in the United States. Rainbow trout run a distant second with 27,504 metric tonnes of production in 2005 (United States Department of Commerce 2007).

2.5.2 Tilapia

Maar *et al.* (1966) indicated that the first attempts to culture tilapia occurred in Kenya in 1924, followed by the Congo in 1937. Pond trials were initiated in Zambia in 1942 followed by Rhodesia in 1950. While native to Africa and a portion of the Middle East (Philippart & Ruwet 1982), tilapia were introduced to parts of Southeast Asia in the 1930s and are thought by today's inhabitants of such nations as the Philippines to be native. The majority of the tilapia produced for human consumption are in the genus *Oreochromis,* with Nile (*O. niloticus*) and blue (*O. aureus*) and red hybrid tilapia (produced from various crosses) being the most popular. Mozambique tilapia (*O. mossambicus*) are still produced in some countries but are no longer the most highly preferred species by culturists. Mozambique tilapia were introduced to the United States in the 1960s (Stickney 1996) followed by various other species, including blue and Nile tilapia. One or more species were later spread into various countries in Latin America and the Caribbean region often by scientists involved in foreign aid projects in the tropics aimed at increasing the human food supply. Rural farmers could easily be taught to rear tilapia and could do so without the need for any sophisticated methods or technology. In addition to being easy to produce, tilapia are usually readily accepted by consumers. Most of the distribution of tilapia around the world was made before issues associated with exotic introductions developed.

Stunting and overpopulation are significant negatives associated with tilapia pond culture. Hand sexing is possible once the fish reach the appropriate size

but is time consuming and subject to human error. One means of dealing with the problem was found the 1960s when monosex populations of tilapia were produced in Israel through hybridization (Sarig 1989). Following that breakthrough, Israeli fish culturists began using tilapia in polyculture with carp and mullet. The creation of all-male tilapia populations by feeding small amounts of male sex hormone to fry tilapia was developed in the 1970s (Guerrero 1975).

Over a period of several years a genetically improved farmed tilapia (GIFT) strain was developed through selective breeding. The effort, largely conducted in the Philippines, has produced fish of exceptional quality and rapid growth that have been widely distributed across the world including back to Africa, the natal home of tilapia. While there is some production of tilapia in the United States—7,803 metric tonnes in 2005 (United States Department of Commerce 2007)—that production cannot begin to meet the demand that has developed in the nation in recent years and continues to grow. Most of the United States experiences winter temperatures that are lethal to tilapia, which limits locales where the fish can be produced year-round to the southernmost regions and Hawaii, with the exception of places that have access to warm water (geothermal or from an industrial source such as power plant cooling water). Considerable numbers of tilapia are being produced in Idaho using geothermal water in a state where the air temperature is well below freezing during extended periods in the winter (fig. 2.3). There is also seasonal production of tilapia in ponds in certain areas of the United States as well as indoor production in recirculating systems. Much of the tilapia imported to North America comes from the Caribbean and

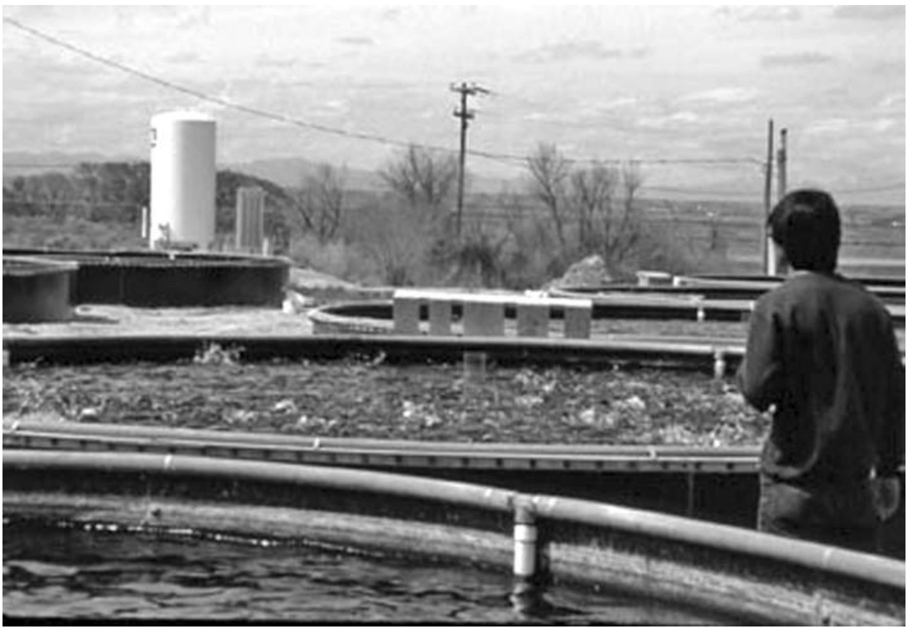

Figure 2.3 Tilapia tank culture facility near Boise, Idaho, uses geothermal water to maintain the proper temperature in a high-temperate climate. (Photo by Robert R. Stickney)

Latin America, and recently, China. Details of tilapia culture in the Americas can be found in a two-volume set of books edited by Costa-Pierce & Rakocy (1997, 2000). Tilapia are produced on a large scale in many Southeast Asian nations. A good deal of effort has gone into tilapia culture in Africa, largely on an artisanal scale.

2.5.3 Flatfish

Publications began to appear in Europe in the late 1800s and early 1900s with respect to plaice (*Pleuronectes platessa*), sole (*Solea solea*), turbot (*Scophthalmus maximus*), and perhaps other flatfish species (Dannevig 1897, 1898; Malard 1899; Fabre-Domergue & Bietrix 1905). Those studies demonstrated that flatfishes could be spawned and reared under hatchery conditions. Additional rearing studies associated with plaice were conducted in later years (Dawes 1930; Rollefsen 1939). The short paper by the latter author also involved plaice hybrids (*P. platessa* × *P. pseudoflesus*) and appears to have been the first to show that brine shrimp could easily be reared as food for fish larvae.

In the late 1940s there was a report on marine fish rearing from the west coast of the United States that included flatfish (McHugh & Walker 1948), while Japan became involved in the culture of flatfish by the mid-1950s (Kurata 1956).

Activity in conjunction with European flatfish culture increased and major advances were made in the 1960s and 1970s. Nash (1968) described his attempts to rear plaice and sole in the thermal effluents of power plants and reported on the best rearing temperature range for each species. A series of publications on plaice rearing in Britain appeared in the 1960s (e.g., Shelbourne 1963a–c; Riley & Thacker 1963; Shelbourne *et al.* 1963, 1964). Cowey *et al.* (1970a, b, 1971) conducted early work on the nutritional requirements of plaice, while Kirk & Howell (1972) described the growth and food conversion rates of plaice fed prepared and natural feeds. An annotated bibliography on attempts to rear marine fish larvae in the laboratory, which included flatfish, was written by May (1971) and a partially annotated bibliography on flatish was produced by White & Stickney (1973a).

With the foundations of flatfish culture having been laid, research activity grew rapidly and additional species were the subject of investigation. Many of them are shown in table 2.1. Citations on research are too numerous to include here but many references to each of the species can be found in Stickney (1997d), which covers the period from the late 1970s to 1997, and in Stickney (2005). For an extensive bibliography focused on Atlantic and Pacific halibut, see Stickney and Seawright (1993), which captures some of the research that led to development of the commercial halibut culture. A special issue of the journal *Aquaculture* is a collection of papers on the culture of flatfish that includes species under study as possible candidates for culture (Stickney *et al.* 1999).

The first author's involvement with flounder culture began in the early 1970s at the Skidaway Institute of Oceanography in Savannah, Georgia USA with

Table 2.1 Species of flatfish that have been the focus of aquaculture research, enhancement stocking, and/or commercial culture, along with country or region of greatest interest or research activity.

Scientific Name	Common Name	Region/Country
Ammotretis rostratus	Longsnout flonder	Indo-Pacific
Heteromycteris japonicus	Bamboo sole	Japan
Hippoglossus hippoglossus	Atlantic halibut	Norway, North America
Hippoglossus stenolepis	Pacific halibut	United States
Kareius bicoloratus	Stone flounder	Japan
Limanda punctatissima	Longsnout flounder	Japan
Limanda yokohamae	Marbled sole	Japan
Liopsetta putnami	Smooth flounder	United States
Microstomus kitt	Lemon sole	Europe
Paralichthys spp.	Chilean flounder	Latin America
Paralichthys adspersus	Fine flounder	Latin America
Paralichthys californicus	California halibut	United States
Paralichthyts dentatus	Summer flounder	United States
Paralichthys lethostigma	Southern flounder	United States
Paralichtys microps	Smalleye flounder	Latin America
Paralichtys olivaceous	Olive flounder[a]	Japan
Platichthys flesus	European flounder	Europe
Pleuronectes ferrugineus	Yellowtail flounder	United States
Pleuronectes platessa	Plaice	Europe
Psuedopleuronectes americana	Winter flounder	United States
Rhombosolea tapirina	Greenback flounder	Australia New Zealand
Scophthalmus maximus[b]	Turbot	Europe
Scophthalmus maeoticus	Black Sea turbot	Europe
Solea solea	Sole	Europe
Verasper variegates	Spotted flounder[c]	Asia

[a] Also known as the Japanese flounder and bastard flounder.
[b] *Psetta maxima* is synonymous.
[c] Also known as the barfin flounder.

support from a Sea Grant project to culture southern and summer flounders. Postlarvae were captured from a tidal river since the technique for spawning the species of interest had not been developed. The methodology for spawning southern flounder was published by Arnold *et al.* (1977).

One result of the experiments was development of ambicoloration in tank-cultured flounders (Stickney & White 1975). A study was conducted on the effects of salinity on southern flounder growth (Stickney & White 1973). There was also a report on the occurrence of lymphocystis in cultured flounder (Stickney & White 1974). A manual on flatfish rearing was produced by White and Stickney (1973), which included information from the literature, but also development of the flounder culture system at Skidaway, which included secondary filters and UV sterilization to reduce the chances of disease organisms entering the system with the incoming water. The manual also discussed collection of postlarvae and juveniles, first feeding of postlarvae with brine shrimp and later conversion to chopped frozen shrimp, then freeze-dried shrimp, and

Table 2.2 Atlantic halibut production in Europe annually from 1998–2005 in metric tonnes (Federation of European Aquaculture Producers 2006).

Year	1998	1999	2000	2001	2002	2003	2004	2005
Production	20	503	135	389	350	84	855	905[a]

[a] Estimated.

finally prepared feeds. Summer flounder were grown from less than a gram to approximately 130 g in 24 weeks during 1972 and to about 120 g in 20 weeks during 1973.

What basically led to the discontinuation of the research on flounders at Skidaway was the fact that they were worth only about US$0.55/kg. The possibility of rearing them profitably appeared to be remote. Interest arose once again in the 1990s as flounder stocks along the east coast of the United States and in the northern Gulf of Mexico became depleted and the value of flounders in the marketplace had greatly increased. Various research groups began producing information after about a twenty-year hiatus. Summer flounders were first stocked in commercial quantities in offshore cages by the University of New Hampshire's Atlantic Marine Aquaculture Center in 1999 (Atlantic Marine Aquaculture Center 2007a).

Research on Atlantic halibut culture was initiated in the mid-1980s, initially in Norway and Iceland, and later in the Maritime Provinces of Canada and in Maine and New Hampshire in the United States. Commercial culture in Europe began in the late 1990s, with Norway and Iceland being the producing nations. Production figures for 1998 to 2005 are presented in table 2.2. A commercial hatchery in Nova Scotia, Canada was the source of fingerlings stocked into an offshore cage off New Hampshire by the Atlantic Marine Aquaculture Center (2007b) and grown for two years from an average of 7.6 cm to weights of 3.2 to 4.1 kg.

The amount of research that has been conducted on Pacific halibut pales in comparison with that on the Atlantic species (Stickney 1997d, 2005). To date, there is no commercial Pacific halibut culture and no indication the situation will change in the near future.

2.5.4 Atlantic salmon

Salmon hatcheries were present in both North America and Scotland by the end of the nineteenth century (Laird 1996). The first in North America was built in 1866 in Ontario, Canada. The Craig Brook salmon hatchery in Maine USA was established a few years later in 1871 (Kirk 1987). Many hatcheries were constructed after the establishment of the United States Commission on Fish and Fisheries in 1872. Until 1965, when the first salmon cage farm was established in Norway (Laird 1996), production was aimed at replacement or enhancement, and in relation to the United States Commission also in attempts to establish populations in areas where the fish were not native.

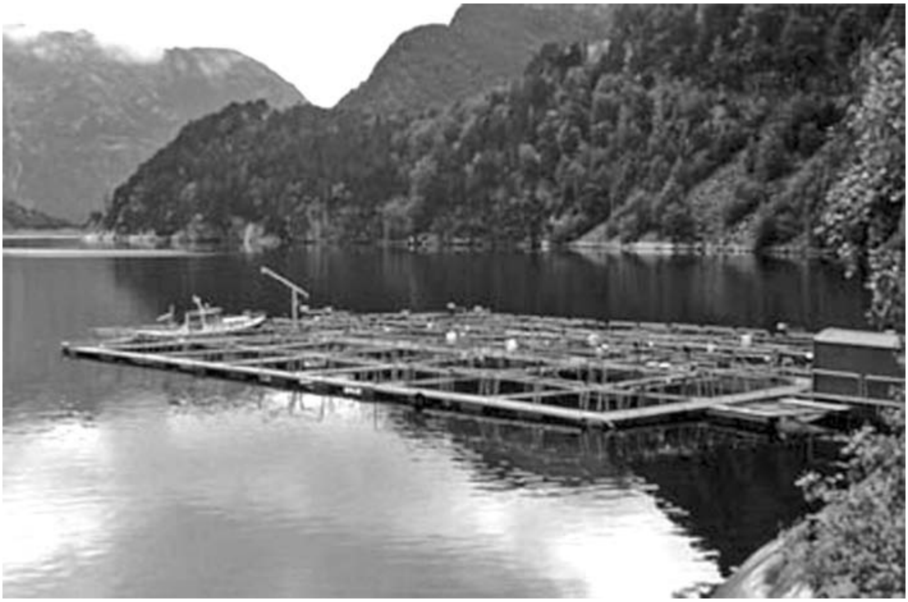

Figure 2.4 Atlantic salmon net pen culture facility in a Norwegian fjord (Photo by Robert R. Stickney).

Salmonid foodfish production in Norway actually began with the culture of rainbow trout introduced from North America, but in the mid-1960s Norwegian fish farmers turned to Atlantic salmon, which was deemed to be more profitable (Tilseth *et al.* 1991). Various types of sea enclosures, beach enclosures, and cages were in production by the late 1970s. In Norwegian fjords, salmon culture facilities today use net pens (fig. 2.4). The 287 Norwegian salmonid farmers in 1973 produced 171 metric tonnes of salmon and 101 metric tonnes of rainbow trout. By 1989 there were 791 farmers responsible for a total of over 118,000 tonnes of salmon and trout (Tilseth *et al.* 1991), with salmon accounting for the majority. Norwegian production rose from about 4,000 metric tonnes in 1980 to 200,000 metric tonnes in 1994 (Laird 1996). Norway was producing about 70% of the world's farmed salmon in 1989 (Tilseth *et al.* 1991).

In North America, Atlantic salmon net pen facilities had been established on both coasts by 1990. Commercial culture occurs in the Maritime Provinces of eastern Canada and in British Columbia in the west. In the United States, salmon are produced in Maine and Washington. The production is primarily Atlantic salmon in Washington and exclusively Atlantic salmon in Maine. There are some Coho and Chinook salmon being produced in Washington and British Columbia.

Atlantic salmon were also being produced in Scotland, Australia (Tasmania), Chile, and the Faroe Islands by 1990. Chile has been on a trajectory to reach the production levels of Norway within the foreseeable future, however recent disease problems and environmental degradation concerns have arisen, which may forestall that from taking place.

Figure 2.5 Salmon net pens in Japan near a resort hotel.

Atlantic salmon hatcheries and smolt rearing facilities are land-based and typically use flow-through tank technology for smolt production. Smolts are typically stocked into marine facilities at around 40 g. Those facilities are for the most part net-pens located in protected coastal areas (fig. 2.5). The technology for open ocean production has been developed but is currently being utilized more for the production of marine fishes rather than anadromous Atlantic salmon. That situation may change in the future as the carrying capacity of protected coastal waters is reached, and as already has been the case in some areas, surpassed.

Ocean ranching of Pacific salmon is practiced in the state of Alaska USA. Pacific salmon farming and ranching is also practiced in the northern part of Japan. The ocean ranching activity in Japan is focused on chum salmon (*O. keta*). Salmon culture and ranching also occurs in Russia (Dushkina 1994).

2.5.5 Additional species and regions

At the risk of leaving out a number of important species and centers of activity, the mention of several additional commercially cultured finfishes and production centers is appropriate. Space does not permit further elaboration; however, interesting stories could easily be developed about how culture methods and technologies were developed around each of the species mentioned.

European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*) are produced in most countries bordering the Mediterranean Sea (Rad

2007). Red sea bream (*Pagrus major*) are cultured in Japan, which is also known for the culture of yellowtail (*Seriola quinqueradiata*).

Tuna (*Thunnus* sp.) are cultured in the Mediterranean using the approach of collecting several kilogram juveniles in purse seines and hauling them to net pen facilities for growout to tens of kilograms over a period of several months. That approach is also used in Australia and on the Pacific coast of Mexico. This production method is covered in more detail in Chapter 7.

Walking catfish of various species in the genus *Clarias* are being produced in Southeast Asia, India, parts of Europe, and various nations in Africa, as well as in Hawaii USA. Most walking catfish are produced in ponds. Those are often constructed with vertical levees and may have low fences around them to keep the fish from escaping.

Carp of various species continue to be the primary finfishes produced in the world (FAO 2006), with China leading the way by a considerable margin. While once favorites throughout the country, carp consumption is now largely confined to rural areas in China since the emergence of a middle class in the cities that is populated by people who have a preference for higher value fishes.

The Indian carp species known as catla, mrigal, and rohu are cultured on the Indian subcontinent. Together, carp and other cyprind species accounted for over 18 million metric tonnes of aquaculture production in 2004 (FAO 2006).

Rainbow trout were mentioned above with respect to their production in Norway having largely been displaced by Atlantic salmon. Rainbow trout are also cultured in many other nations, including seemingly unlikely places such as Nepal, New Zealand, and South and Central America. Rainbow trout were shipped to New Zealand from the United States, along with Chinook salmon, over 100 years ago. New Zealand has prohibited the import or sale of rainbow trout either live or processed to avoid the introduction of diseases to the trout that exist in the island nation today as a result of the century old introductions. In the United States, 95% of the trout that reach the market are produced in the Hagerman Valley of Idaho.

Striped bass (*Morone saxatilis*) and striped bass hybrid (*M. saxatilis* × *M. chrysops*) culture is confined to the United States, while red drum (*Sciaenops ocellatus*), native to the Gulf of Mexico and southeastern United States, are being cultured in parts of Asia. Cobia (*Rachycentron canadum*) is also being cultured in parts of Asia and is of interest to culturists in the United States and in the Caribbean region. Interest in pompano (*Trachinotus carolinus*) culture has redeveloped after a hiatus since the 1970s when research was conducted in Florida. There had been interest in the culture of dolphin (*Coryphaena hippurus*, which is a finfish, not a mammal, and is marketed as Mahi Mahi) in the past, but there appears to be little activity associated with its culture at present.

Milkfish (*Chanos chanos*) are cultured in Southeast Asia (particularly in the Philippines) and mullet (primarily grey or striped mullet, *Mugil cephalus*) are cultured in many parts of the world, including the Mediterranean region and Southeast Asia.

With the collapse of the cod (*Gadus morhua*) fishery in the western north Atlantic and severe declines in the eastern north Atlantic, cod aquaculture has

become the focus of commercial ventures in Norway, Canada, and Maine, in the Unites States.

A variety of native species in Brazil are currently being cultured to at least some extent, while many others may be suitable candidates for fish culture and have yet to be evaluated in that context. The same is undoubtedly true for other species in Latin America.

Finally, Australia is a nation that is developing a variety of cultured foodfish species. One that is quite popular is the barramundi (*Lates calcarifer*).

In Hawaii, local finfish species are sold under their Native Hawaiian names. Two fishes, kahala (amberjack or Hawiian yellowtail, *Seriola* sp.) and moi (Pacific threadfin, *Polydactylus sexfilis*), are being cultured and are available in restaurants and in processed form for tourists interested in taking some back to from whence they came.

Unlike domestic livestock production, which today and for centuries, has relied on a handful of species, the number of fish species under culture has been growing for a few decades and there is no end in sight. Many of the ones of particular interest are marine species with extremely small eggs and larvae, making them difficult to feed after yolk sac absorption. Atlantic and Pacific halibut, which can reach sizes of 200 kg or more, are among the species with tiny eggs. Not only are the eggs small, they are extremely fragile. It is testimony to the resourcefulness and tenacity of those who have developed industries around such species that they have achieved the level of success that is seen today. Other species elude the talents and technology to bring them into commercialization, but breakthroughs will be made and new species can be expected to appear on the tables of restaurants and in the supermarkets and fish markets of the world bearing a label indicating that they were cultured.

2.6 Shrimp culture

Shrimp aquaculture has its origins in Southeast Asia, where for centuries farmers raised incidental crops of wild shrimp in tidal fish ponds, but the shrimp were not considered of value. The earliest record of Penaeidae is in Chinese history and traces back to the eighth century BPE. Japanese literature referred to penaeids in 730 BPE. The first scientific record of a penaeid was in 1759, when Seba of Amsterdam named and sketched a penaeid. In 1815, Rafinesque recognized that penaeids were a distinct group within the Decapoda.

Artisanal capture of freshwater shrimp was probably incidental to pond fish culture in some locations. Spawning, larval rearing, and growout of freshwater shrimp was not developed until the twentieth century.

2.6.1 Marine shrimp

Documentable shrimp culture began in 1933, when Japanese biologists, including Motosaku Fujinaga (who also published as Hudinaga), first studied

(Hudinaga 1935) the artificial propagation and culture of the Kuruma shrimp, *Penaeus japonicus,* now referred to as *Marsupenaeus japonicus.* A graduate of Tokyo University, Fujinaga entered the Hayatomo Fisheries Institute of the Kyodo Gyogyo Company at Oyanoshima, Amakusa (later called the Nippon Suisan Company), and worked as a biologist (Tseng 1987). There were only three people assigned to conduct the work under very primitive conditions in a small lab with no electricity and only kerosene lamps for light.

In the first year, Fujinaga used a plankton net to collect juvenile shrimp and studied their morphology, taxonomy, and life cycle. However, he was not able to obtain eggs using that method of collection. He then placed mature spawners in aquaria to obtain eggs. Nauplii were obtained but died when they were not fed properly and failed to metamorphose into zoea. A series of feeding trials were conducted over the next several years. It was not until 1939 that Fujinaga successfully fed shrimp larvae the diatom *Skeletomema costatum,* which came from a mass culture technique developed by Matsue of Tokyo University.

Fujinaga (Hudinaga) published from 1935 to 1969 and conducted pioneering shrimp research for more than forty years (Hudinaga 1935, 1941; Fujinaga 1969). He set up a pilot commercial hatchery in 1959 that was instrumental in transferring the technology to the commercial sector, and in the early 1960s the first commercial farms were built along the Seto Inland Sea of Japan. By 1967 some twenty operations using his methods produced 4,000 metric tonnes of shrimp from 8,500 ha of water. Dr. Fujinaga was given the name "Founder of Kuruma Shrimp Culture in Japan." The next real breakthrough in mass culture of shrimp larvae came later, when Fujinaga was credited with feeding *Artemia* nauplii to postlarval shrimp and increasing their survival and health (Tseng 1987).

While the Asian (Japanese and later Taiwanese) approach to larval shrimp culture was considered the green water method (most feeds such as algae were grown in the same large volume, deep tanks with the shrimp larvae), another method of shrimp culture was developed in the Western hemisphere. The Galveston method, or clear water method, was developed in Galveston, Texas. Shrimp larval feeds were grown in separate tanks and fed when needed. This was generally synonymous with smaller, conical tanks with heavy aeration to keep everything suspended, clearer water in batch culture operation, higher stocking densities, higher larval survivals, and higher labor requirements.

Limited studies of penaeid shrimp had been conducted in the United States in the 1930s, and even though none were aquaculture oriented, they added to the knowledge base on penaeids. In 1935 J.C. Pearson described the eggs of some species of penaeid shrimp, and he described the life histories of some American penaeids (Pearson 1939). In 1953, Paul E. Heegaard attempted to spawn the white shrimp, *P. setiferus,* in Port Aransas, Texas, and Gunter and Hildebrand worked with the wild shrimp life cycle in 1954 (Gunter & Hildebrand 1954). About that time the Bureau of Commercial Fisheries, later named the National Marine Fisheries Service, began to work with the biology of commercial shrimp in the Gulf of Mexico. According to Harry Cook (Treece 1993) the Director of the Laboratory, Milton J. Lindner, was successful in obtaining the funding

necessary to develop the methodology for a prototype shrimp hatchery system at the Galveston Laboratory. In 1959 Harry Cook was a biologist for the Bureau of Commercial Fisheries and the following account is from an oral interview with Harry Cook by Bob Rosenberry of Shrimp News International (2007). Papers related to these developments include Cook (1965) and Cook and Murphy (1971).

Three other people were hired to study the life history of Gulf of Mexico shrimp. Wooden troughs about 0.75 m by 1 m in diameter were used as rearing containers. When the research started they had trouble finding gravid brown shrimp *(Penaeus aztecus)* so they worked with *Xiphopenaeus* and published a paper that described the nauplius stage. Later the researchers were able to spawn brown shrimp and they sketched the various larval stages so that they could identify them in seawater samples. They published the life history of the brown shrimp and a key to the genus. There were researchers in the red tide section of their lab who knew how to culture algae. They relied heavily on the work of Fujinaga but their initial attempts were unsuccessful. The algae and debris would settle and the larvae would concentrate in the corners. The investigators were growing larval feeds in inverted carboys and saw how the water circulation kept everything suspended and the debris from clumping. They decided to rear the larval shrimp in fiberglass tanks with conical bottoms with an air stone at the bottom of the cone and around the sides of the tank. They also developed a filter system that allowed water exchange without damaging the larvae. Cook had visited an oyster hatchery on Long Island, New York, that was using airlifts in its algae tanks. When Cook returned to Texas he put airlifts in the tanks and that basically became the Galveston method: tanks with conical bottoms, airlifts for aeration, a daily batch exchange of water and the addition of live feed, either a mixture of *Skeletonema and Monochrysis* for zoea or brine shrimp for mysis and postlaravae (Cook 1965; Cook & Murphy 1971). Although the conical tanks are rarely seen now, this general method is still in use today in many Western hemisphere hatcheries. The Galveston method generally used a number of different algal feeds but eventually evolved into a combination of small cell algae and larger cell algae (*Chaetoceros* sp. and *Tetraselmis chui*) as beginning feeds for shrimp larvae.

At that same time in Florida, Tom Costello and Don Allen at the Miami Lab of the Bureau of Commercial Fisheries used fluorescent light bulbs to grow algae indoors. At the Galveston laboratory, researchers were growing algae in outdoor greenhouses, but eventually fluorescent bulbs and indoor culture became part of the Galveston method (Rosenberry 2007). Also as part of the development of the Galveston method, a variety of food types, such as rotifers and nematods were tried, but they eventually were dropped and replaced by *Artemia* as food for late stage larval shrimp.

The water in the closed seawater system at the Galveston laboratory had a mineral imbalance that became a major problem. In England, a researcher reported better production when using EDTA in algal cultures so the Galveston group tried it and made a major breakthrough. EDTA is a chelator that helps improve water quality by helping the minerals and metals stay free and unbound. With the success of EDTA in algae culture they decided to put it in the shrimp

tanks and that's when they started getting better larval survival. The Galveston group did not count the algae; they used a spectrometer to get an estimate of algal density.

Another procedure developed in the Galveston method involved replacing the volume removed from the algae cultures to feed the larval shrimp each day with sterilized water and nutrients, so that the algae would grow back to optimum density by the next day. This kept a continuous, clean source of food available for the shrimp with minimal effort and expense.

Although the Japanese research had some influence on the research in Texas, Fujinaga's and Mitsutake Miyamura's visit to the Galveston lab in 1963 was not for the purpose of information transfer and was not a turning or beginning point for shrimp culture in Texas as we were led to believe for many years by various historical accounts. According to Harry Cook (personal communication, 1992) the purpose for the Japanese visit (which only lasted a few hours) was to find a place for shrimp growout in the United States The Japanese wanted to lease East Matagorda Bay, Texas, for that purpose but ended up in Florida and in 1967 established Marifarms, Inc., which operated from 1968 to 1982. A full account of those activities was published by John Chesire (2005). Storm damage and other problems including environmental concerns led to moving from the United State to Ecuador (Treece 1993).

J. J. Ewald worked on the laboratory rearing of pink shrimp *P. duorarum* in 1965 (Ewald 1965). Harry Cook described the rearing and identification of Gulf of Mexico native shrimp larvae in 1965, published about a dozen other papers on the subject from 1966 to 1970, and Cook and Murphy described the developmental stages of native shrimp larvae in 1971. It wasn't until after Cook left the Galveston lab that other researchers further developed maturation techniques for shrimp (Rosenberry 2007, interview with Harry Cook). A newcomer (Cornelius Mock) came to the National Marine Fisheries Service laboratory about the time Harry Cook was leaving and Mock continued to publish on the Galveston Method.

Generally speaking, in the past the Western hemisphere practiced the Galveston method in company-owned hatcheries that supplied large farms. At the same time, culturists in the Eastern hemisphere practiced the green water or Taiwanese method in smaller, but more numerous, usually family or government-owned hatcheries. However, in recent years the two major methods of larval rearing have merged. The small backyard hatcheries in Asia further blurred the distinction of the two methods. In Asia small and medium-scale hatcheries continue to be most popular but worldwide, the distinction between the two methods or styles of larval culture continues to be more blurred as new operations are built, borrowing the best from both methods.

Commercial shrimp growout attempts were made in Ecuador in the 1960s and in the United States starting in the late 1960s and early 1970s. The Ecuadorian industry was based upon *L. vannamei* and *L. stylirostris,* and was started by accident when a broken dike on a banana farm allowed shrimp to enter the farm. By the time the farmer repaired the dike a crop of shrimp had been produced. Expansion of the Ecuadorian industry was made possible by an abundance of wild

postlarval shrimp. After the industry matured and could not rely entirely upon the seasonally wild-caught postlarvae, brood collection stations were developed along the coast, which captured and spawned wild-mated females and provided an important nauplii source to meet the growing hatchery demand. The Ecuadorian industry became more dependent upon hatcheries as it grew and larvae from hatcheries became stronger when new hatchery techniques and combination diets were developed. The initial United States industry followed that lead but was based on native species of white, brown, and pink shrimp (*Litopenaeus setiferus, Farfantepenaeus aztecus,* and *F. duorarum,* respectively). When researchers in the United States grew exotic shrimp from the Pacific coast of Central and South America, those species proved to be easier to culture and more productive in the ponds. Gradually commercial producers concentrated on exotics such as *L. vannamei,* now the most popular farm-raised shrimp in the world.

Once shrimp hatcheries began supplying large quantities of shrimp to farmers, the production of farm-raised shrimp expanded rapidly worldwide. The explosion of the industry continued into the early 1990s until problems began with disease outbreaks and water quality deterioration, which slowed worldwide production for a few years. Many groups from different countries worked on shrimp culture research and development. SEAFDEC (the Philippines), TASPAC/MEPEDA (India), AQUACOP (France and Tahiti), NOAA/Sea Grant and USDA/USMSFP (US), Ralston Purina, DOW Chemical, Coca Cola, W. R. Grace, Prince, King James Shrimp, (US companies), Marifarms, Inc. (Japanese-American owned in Panama City Florida and later Ecuador), Sea Farms (Honduras), and United Nations/FAO (Rome, Italy) are just a few groups that made progress on shrimp culture through research.

In addition to Japan, Taiwan became a very successful shrimp producing country in Asia. In 1969, Taiwan began to culture a number of economically important species of shrimp (Lien & Ting 1969). In 1970, with financial aid from the Rockefeller Foundation the Tung Kang Marine Lab was established and led the way to establishing *P. monodon* in Taiwan and other parts of Asia. I-Chiu Liao, a follower of Fujinaga, worked many years at the Tung Kang Marine Lab with *P. monodon* and is known as the "Father of *monodon*" in Taiwan. By 1978 most of the farmers in Taiwan had mastered the culture techniques and in 1979 the production in Taiwan reached a historical peak of 600 metric tonnes. By 1986, the production was up to 45,000 metric tonnes in Taiwan alone. Production crashed in 1988, when farms experienced severe disease outbreaks of Monodon Baculovirus (MBV) caused by their own activities that had led to environmental degradation. The problem caused a near collapse of the industry in Taiwan and the high production levels of 1986 were never again reached.

However, the success in Taiwan with *P. monodon* spread to other areas in Asia. The Philippines, Hong Kong, Malaysia, Singapore, Sabah, Borneo, Southern China, Thailand, and Australian shrimp industries developed rapidly. In 1985 there were 148,000 metric tonnes of shrimp produced in Asia (Scura 1987).

Shrimp culture became an organized industry on a worldwide scale and similar culture techniques were applied to various species in different regions. For example, *P. orientalis* (later named *Fenneropenaeus chinensis,* a colder water

species) was grown in China; *P. japonicus* in Japan; *P. monodon* in Taiwan and the Philippines; *P. merguinsis* in Thailand, Indonesia, and parts of China; *Metapenaeus ensis* in Hong Kong and other parts of China and *Macrobrachium rosenbergii* in Malaysia, other parts of Asia and Hawaii; and *P. vannamei* and *P. stylirostris* in Ecuador, Mexico, the United States, and other Western hemisphere countries.

In 1997, Isabel Perez Farfante and Brian Kensley (Farfante & Kensley 1997) proposed some changes in the way scientists referred to the popular farmed shrimp species. Except for three species (*Penaeus monodon, P. esculentus,* and *P. semisulcatus*), the genus names were changed for the other penaeids to *Litopenaeus, Fenneropenaeus, Marsupenaeus,* or were based on a reexamination of the phylogenetic relationships among species in the family Penaeidae.

The majority of the shrimp produced for human consumption have historically been grown in Asia (80% Eastern hemisphere—*P. monodon, P. chinensis,* and others—and 20% Western hemisphere—*P. vannamei, P. stylirostris,* and others). Diseases caused a collapse of the industry in both hemispheres (IHHN virus, Monodon Baculovirus, Yellowhead virus, Taura Syndrome Virus, White Spot Syndrome Virus, and others) first in the Eastern hemisphere and later the Western hemisphere. The estimated economic loss in Taiwan (1987–1988) was US$420 million; in China (1993) US$1 billion; and in Thailand (1991) US$180 million (NACA 1994–1995). World Bank estimates of shrimp disease losses for all of Asia from 1994 to 1996 ranged from US$1 billion/year to $3 billion/year. In 1999 to 2000, Ecuador, the Western hemisphere's largest shrimp producer at the time, lost US$300 million to $500 million due to viral diseases (Wickins & Lee 2002).

Disease resistant *P. vannamei* replaced diseased stocks once biosecurity techniques were developed and genetic selection of shrimp began. Genetic selection for disease resistant penaeids started on a fast track in the United States in the late 1980s and early 1990s, thanks to the US Department of Agriculture's Marine Shrimp Farming Program and the technology and practice spread to other countries in the mid- to late-1990s. Since disease resistant stocks have been developed and *L. vannamei* culture has grown in both hemispheres, *L. vannamei* has replaced most of the species that were once grown. Once disease resistant stocks of *P. monodon* are more widely distributed, that species may come back as well. A number of companies are now working to make that happen with one US company now promoting and marketing ninth-generation selected animals.

Coupled with disease resistant strains, low salinity stocks were also developed that allowed *P. vannamei* farming in freshwater starting in the mid-1990s. The technology matured in China and freshwater culture of the species was a major driving force behind China's shrimp farming boom in the early 2000s.

According to Lem (2006), shrimp (both freshwater and marine and both harvested and farm grown) is by far the most important commodity by value in the international fish trade. Yearly exports worldwide of shrimp and shrimp products exceeded US$10 billion in 2003 and represented 20% of world total exports of fish and fishery products (FAO 2004). Marine shrimp farming grew into a US$6 billion industry but diseases and lack of biosecurity continue to give the

shrimp-industry problems, even with disease-resistant stocks. Yet each country that experienced a crash in production has started a comeback. Most countries have shifted to genetically improved, domesticated stocks of *L. vannamei* or plan to do so in the near future.

China is the largest marine shrimp farming country in the world and its 490,000 metric tonnes in 2003 accounted for 27% of total world production (Yuan *et al*. 2006). China's shrimp farming industry has continued to grow since 1997. The initial success of *L. vannamei* attracted more and more farmers, resulting in more than a doubling of production in only four years from 218,000 metric tonnes in 2000 to 500,000 metric tonnes in 2004. The US shrimp farming industry started to decline in 2004 and continues a downward trend. To make matters worse, after being funded for twenty-five years, the US Congress terminated the funding of the USDA US Marine Shrimp Farming Program in 2011.

2.6.2 Freshwater shrimp

The Malaysian freshwater shrimp or giant river prawn (*Macrobrachium rosenbergii*) became the subject of aquaculture research and commercial enterprise less than fifty years ago. In 1961 a major breakthrough was achieved at the Marine Fisheries Research Institute, in Glugor, Penang, Malaysia, when it was discovered that a certain amount of salinity was an important basic requirement for the survival, growth, and development of the larval stages of the species (Ling & Merican 1961). The discovery quickly led to other breakthroughs on the food and environmental requirements of the larvae. Techniques for rearing hatchlings through all their larval stages were successfully developed and the first laboratory-reared juvenile was produced in June 1962 (Ling 1977). Techniques for spawning and other hatchery operations were soon developed, and in the spring of 1963 sufficient numbers of juveniles were produced for conducting growout experiments in ponds. Other refinements were reported by Ling (1967a, b). The results of growout experiments were encouraging and news of the achievements spread rapidly to other countries (Tham 1968; Liao & Huang 1972; Racek 1972). According to Ling (1977), growers in Hawaii asked the Marine Fisheries Research Institute for specimens in 1969 and soon became a major producer of *M. rosenbergii*.

Mistakidis (1969) published an excellent biological account of the freshwater shrimp with line drawings of eggs and larval stages. Fujimura & Okamoto (1970) at the University of Hawaii further refined the mass production of juveniles, and thereafter, freshwater shrimp culture began to spread to many other areas. Bardach *et al*. (1972) gave an early account of progress with the species. The growout technology spread to areas such as Mauritius, French Polynesia (Aquacop 1977), Israel, and in the US state of Florida. The Weyerhaeuser Company in Florida started a research and development program in 1974. Culture then began in the Unites States in Texas (1974); Puerto Rico (1975); Martinique, French West Indies (1977); Jamaica and the Dominican Republic (1978); Central America (1979); and Brazil (1981).

Liao *et al.* (1977) in Asia and Johnson (1977) in the Western hemisphere described diseases found in freshwater shrimp. Durwood Dugger assisted Sun Oil Company from 1974 to 1976 with a shrimp project in Texas and he formed a new company, Commercial Shrimp Culture International (CSCI). When CSCI started, Dugger and some CSCI small investors built a freshwater shrimp hatchery called Aquaprawns, Inc. Dugger built, developed, and ran the Aquaprawns hatchery for Sun Oil in Port Isabel, Texas. Aquaprawns had some very small experimental ponds in Brownsville where they were the first company to harvest and transfer freshwater shrimp with a fish pump and weren't the first company to fail to overwinter *M. rosenbergii* in open ponds even with a large heating system in spite of having some of Sun Oil's best engineers working with them. Aquaprawns conducted one of the first large scale *M. rosenbergii* restaurant marketing studies on mainland United States (5,500 mt), and was one of the first to look at aeration and various device efficiencies. After hurricane Allan destroyed the project in August 1980, CSCI received a US Department of Commerce Small Business Administration (SBA) disaster loan for US$300,000 and moved to a 162 ha site in Los Fresnos, Texas, where they rebuilt a multispecies hatchery and grew *M. rosenbergii, P. vannamei,* and *P. setiferus* in Rio Grande irrigation water in a two-phase, twenty-pond project consisting of two hectare ponds and four twelve-meter by sixty-five-meter greenhouse nurseries. CSCI was involved with one of the first commercial uses of head-start shrimp nurseries, and was one of the first groups to grow *L. vannamei* and *P. setiferus* in freshwater in commercial quantities, seeing that *L. vannamei* could adapt better to freshwater than *P. setiferus,* and at the same time produce more kilograms per hectare than with *M. rosenbergii.*

During this time CSCI was selected by the US Army Corp of Engineers (COE) to develop a 121 ha dredge containment area for a marine shrimp farming demonstration on the Brownsville ship channel. However, for political reasons, this COE project was not funded for another two years. Later, from 1988 to 1992 the project was completed under a new name and new group (MariQuest, Inc.) and tried to overwinter cold-tolerant shrimp species from Asia.

According to Durwood Dugger, CSCI commercially marketed the largest quantities of cultured *M. rosenbergii* in the United States to date. That marketing effort proved a number of things about *M. rosenbergii* as a premium seafood product—mainly that the cost of sales in serving the premium seafood market offset any price premiums that might be received on a large-scale commercial basis. After proving they could produce *L. vannamei* in freshwater commercially and that took almost any of the advantages away from *M. rosenbergii* that might be realized, this was Dugger's last effort to try to commercialize *M. rosenbergii* in the United States. The freshwater shrimp operation in Los Fresnos was purchased first by a local businessman (Ted Hollin) and later by Marshall Snider from New York, who operated it a for a few years until an early winter storm killed the shrimp in November 1991. Snider moved his operation to Puerto Rico and continued to supply the New York market.

Durwood Dugger completed a feasibility trial on aquaculture in far west Texas (Pecos County) and Texas A&M University set up a pilot culture system

near Imperial, Texas. Seven farms built commercial operations for brackishwater shrimp in the following years, but only one has survived (Bart Reid's Permian Sea Organics farm in Imperial, a 26 ha facility that cultures *L. vannamei*).

In 1983, Aquaculture Enterprises, Inc., acquired an unsuccessful prawn farm in Puerto Rico (Shrimps Unlimited, Inc.) and John Glude restarted the farm. It experienced a large debt service and construction delays for five years before it was considered economically viable in 1988. Failure to obtain projected production levels led to a change in strategy that was developed and tested in 1989 and 1990 when production of 3,000 kg/ha/yr was achieved. White postlarvae (PL) disease caused by *Rickettsia* hit the company while a recession in the United States caused a drop in demand for the product. Production was put on hold in 1992 (WAS 1994), by which time inexpensive Taiwanese frozen shrimp had appeared in the world market at US$10/kg. This created fierce competition in the industry. For many producers, their production costs were higher than the prices that shrimp were bringing on the market.

Large freshwater shrimp similar to *M. rosenbergii* are found in practically all tropical and subtropical regions. *M. rude* was cultured along with *M. rosenbergii* in India for awhile. The monsoon river prawn, *M. malcolmsonii*, was grown in Pakistan and India; the painted river prawn, *M. carcinus,* in Barbados; *Cryphiops caementarius* in Peru; the oriental river prawn, *M. nipponense,* in China; the African river prawn, *M. vollenhovenii,* in Africa; and species native to the United States (*M. acanthurus*, *M. carcinus*, *M. ohione,* and *M. olfersii*) have been grown but none of the species listed species has been as successfully or as widely produced in aquaculture as *M. rosenbergii*. However, in China, culture of *M. nipponense* has recently experienced very significant expansion.

Polyculture of Chinese and common carp with *Macrobrachium* has been tried (Malecha *et al.* 1981) and early Taiwanese research demonstrated that polyculture of milkfish and grey mullet led to efficient utilization of pond resources (Liao & Chao 1982). Researchers in the Philippines found that *M. lanchesteri* could be polycultured with rice (Guerrero *et al.* 1982). Culture of freshwater shrimp in combination with fingerling catfish was successfully demonstrated under small-scale experimental conditions and appeared commercially feasible (D'Abramo & Brunson 1996). A scheme for intercropping of freshwater shrimp and red swamp crawfish was developed and evaluated as well. Numerous intercropping scenarios involving such species as bait minnows, tilapia, and other fish species have also been evaluated but the monoculture of *M. rosenbergii* is the sustainable method.

There has been a resurgence in the culture of *M. rosenbergii* in the United States in recent years due to researchers in Kentucky and Tennessee finding that cooler temperatures are actually beneficial to growth. Apparently, in warmer climates such as Mississippi and Texas, the animals put more energy into reproduction than growth. There have been several new hatcheries built in the last few years to accommodate that increased growth in the southeastern states. The economics and management of freshwater shrimp culture in the Western Hemisphere were addressed by Valenti & Tidwell (2006).

The Malaysian prawn was introduced into China in 1976 and has become a major freshwater species there with a 20% annual growth rate during the late 1990s. Total farming area exceeds 30,000 ha in China, creating a yield of 97,420 metric tonnes in 2000. Under competition from freshwater *L. vannamei,* farming of *M. rosenbergii* was reduced to 87,252 metric tonnes in 2003, but farming activities still exist in over twenty provinces of China (Yuan *et al.* 2006). China is by far the largest freshwater shrimp producing country. Annual world production of *M. rosenbergii* has reached a volume greater than 300,000 metric tonnes valued at more than US$1.1 billion.

2.7 Mollusk culture

The Greeks apparently were involved in some type of oyster culture by about 350 BPE (Gosling 2003). The Romans reportedly constructed ponds to stockpile European oysters (*Ostrea edulis*) and placed wood fascines (bundles of sticks) on the ponds to collect spat (Herál & Deslous-Paoli 1991). According to those authors, human population increases in Europe led to overfishing of the oyster beds in France, Ireland, and England in the eighteenth century and regulation of the fishery failed to deter the practice. The French refined the Italian fascine technique in about 1860 and also employed other materials such as slate as cultch. Bottom and rack culture were then developed. The French began importing Japanese oyster (*Crassostrea gigas*) spat and adults in 1968 and terminated the process in 1975 after reproduction of the species had become well established. In Japan, oyster farming dates back to 1624 (Gosling 2003).

Oyster culture in the United States ranges from just scattering oyster shell as cultch to spawning and setting spat in a hatchery for distribution to appropriate beds. The oysters may be collected using tongs or dredges subtidally or by hand intertidally. Some tray culture is also practiced. The American or eastern oyster *Crassostrea virginica* is cultured along the Atlantic and Gulf of Mexico coasts and *C. gigas* was first imported from Japan to the Pacific Northwest early in the twentieth century. Annual imports continued until World War II, after which hatchery technology was developed to ensure a constant supply of spat.

Mussel culture in Europe is supposed to have been accidentally initiated in 1225 by a sailor who was shipwrecked along the coast of France (Gosling 2003). He drove poles into the substrate and tied netting around them to attract birds. Mussels soon colonized the poles and were of better quality than those on the bottom. What became the bouchot technique continues to be conducted in France. In Spain, mussels are cultured in large quantities on lines suspended from rafts. Longline culture is another common culture method. In the United States, mussel consumption was low except in places where it was a part of the culture of one ethnic group that settled there. The popularity of mussels has increased dramatically over the past two or three decades and mussel culture has developed to help supply the demand.

Some form of clam culture has been conducted in China for several hundred years but few details appear to be available (Pillay & Kutty 2005). Native hard

clams, *Mercenaria mercenaria* and *M. campechiensis,* are cultured on the east coast of the United States and the Manila clam, *Ruditapes philippinarum,* is cultured in the Pacific Northwest where it was introduced. Clams are cultured on the bottom, and in the Pacific Northwest, intertidal clam beds are covered with netting to reduce predation by benthic predators. The clams are harvested at low tide with mechanical harvesting devices.

While successful spat collection method was developed thirty years earlier, culture of the yesso scallop *Patinopecten yessoensis* began in Japan in the 1960s. Other popular species are *Chlamys* spp., *Argopcten* spp., and *Pecten maximus.* The major scallop-producing nations are Japan and China (Gosling 2003). Culture of at least one species produced in China is said to have been initiated when a shipment of about fifty individuals was sent from the United States several years ago. Much of the export market for those scallops from China is back to the United States.

2.8 Controversy

The history of aquaculture would not be complete without mention of the controversy that swirls around the practice, particularly with respect to marine fishes (including anadromous salmon) produced in coastal or offshore facilities. Opposition to fish culture in the commons first appeared in the United States in the 1980s. It seems to have initially been largely an issue with upland homeowners in the Puget Sound region of Washington State who objected to what they called visual pollution from net pen salmon farms. Interestingly, while fish culture operations in Washington were seen as eyesores, their counterparts in Japan were considered amenities because they are producing highly desirable food items. In the United States, Canada, and part of Europe, opposition to aquaculture sprang up wherever fish farming was initiated in public waters. Over time, a laundry list of issues was developed. Even in areas where rigorous permitting processes were put into place, opponents were often able to tie up the permitting process for months or even years by raising objection after objection, often to the point that the prospective fish farmer spent all the resources allotted for establishing the fish farm on lawyer fees.

While the controversy has slowed marine fish culture development significantly, at least some of the issues raised by opponents do need to be addressed. It is certainly the case that there have been instances where fish farms have been stocked too heavily in a given area and the carrying capacity has been exceeded. This has caused considerable negative impact on the local environment. That happened, for example, in Japan during the 1970s. For approximately the last two decades a considerable amount of research has been conducted to determine which objections have merit so best management practices or new approaches could be developed to address the problems. Technology has also been advanced in terms of cage designs for offshore systems that will better withstand storms and prevent escapes.

A major issue has been the use of fish to feed fish. To provide the proper amino acids and fatty acids, fish meal and fish oil have long been employed as ingredients in fish feeds. In recent years a considerable amount of work has been conducted to find alternative protein sources to replace fish meal and the percentage of fish meal in many feeds has been reduced. Plant sources of n-3 fatty acids, including sources from genetically modified plants, are alternatives to fish oil in fish feeds and may ultimately completely replace fish oil. Fish nutritionists have also been looking for ways to improve phosphorus digestibility in fish feeds to reduce the potential for eutrophication.

Proper siting of aquaculture facilities in public waters is critical for avoiding issues associated with eutrophication and the creation of anoxic areas under cages due to buildup of feces and uneaten feed. Maintaining appropriate densities of fish in cages can also help ensure water quality as well as reducing stress on the fish and possibly reducing the potential for diseases.

Adoption of new technologies and research results by the industry not only lead to more increased profitability, but also improvement in the sustainability of marine fish culture enterprises. It is certainly not in the best interest of the fish farmer to cause environmental damage because it will also be the farmer that suffers.

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